

# **Salton Sea Ecosystem Restoration Plan Inflows/Modeling Working Group**



**September 16, 2005  
San Diego, CA**

# **Agenda**

- ◆ **Recap of previous meeting**
- ◆ **Overview of hydrologic modeling objectives**
- ◆ **Summary of model capabilities and limitations**
- ◆ **Generalized CALSIM software overview**
- ◆ **Enhancements incorporated for Salton Sea model**
- ◆ **Salton Sea model formulation**
- ◆ **Model demonstration and usage**
- ◆ **Deterministic vs stochastic applications**
- ◆ **Future model development tasks**
- ◆ **Discussion**

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# **Recap of Previous Meeting**

- ◆ **Historic inflows**
- ◆ **Projected inflows for No Action**
- ◆ **Approach for addressing future uncertainty**
- ◆ **Projected inflows considering future uncertainty**
- ◆ **Historic and projected salt loads**
- ◆ **Hydrologic model update**

# **Hydrologic Modeling Objectives**

- ◆ **Provide tool for hydrologic and salinity analysis of Salton Sea alternatives to measure performance towards goals and trade-offs**
- ◆ **Provide information to assist in alternative configurations and designs**
- ◆ **Evaluate Salton Sea impacts due to hydrologic uncertainty**
- ◆ **Publicly-available, documented analysis tool**
- ◆ **Facilitate consistency of data**
- ◆ **Serve as an analysis tool beyond the ERP**
- ◆ **Suite of models may be necessary**

# **Hydrologic Model Requirements**

- ◆ **Simulate future Salton Sea elevation and salinity under varying configurations and inflow assumptions**
- ◆ **Account for full water and salt balances**
- ◆ **Monthly and/or annual time steps**
- ◆ **Incorporate multiple impoundments and major components or processes of likely alternatives**
- ◆ **Optimize for simultaneous solution of elevation and salinity targets**
- ◆ **Incorporate functional relationships of evaporation suppression with increasing salinity, salt precipitation, and salt re-dissolution**
- ◆ **Stochastic simulation capability**

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# Summary of Model Capabilities

- ◆ SALSA model is application of CALSIM to the Salton Sea
- ◆ Test networks and “real” networks developed and simulated
- ◆ Generalized model elements
  - Open water storage elements (SEA)
  - Natural treatment systems (NTS)
  - Mechanical treatment systems (MTS)
  - Habitat wetlands (HAB)
  - Air quality management (AQM) areas
- ◆ Consumptive demands computed for NTS, HAB, and AQM elements
- ◆ Salt balance algorithm added to model
- ◆ Delivery, elevation, and salinity targets achieved
- ◆ *Monthly* simulation for 75 years

# **Summary of Model Capabilities**

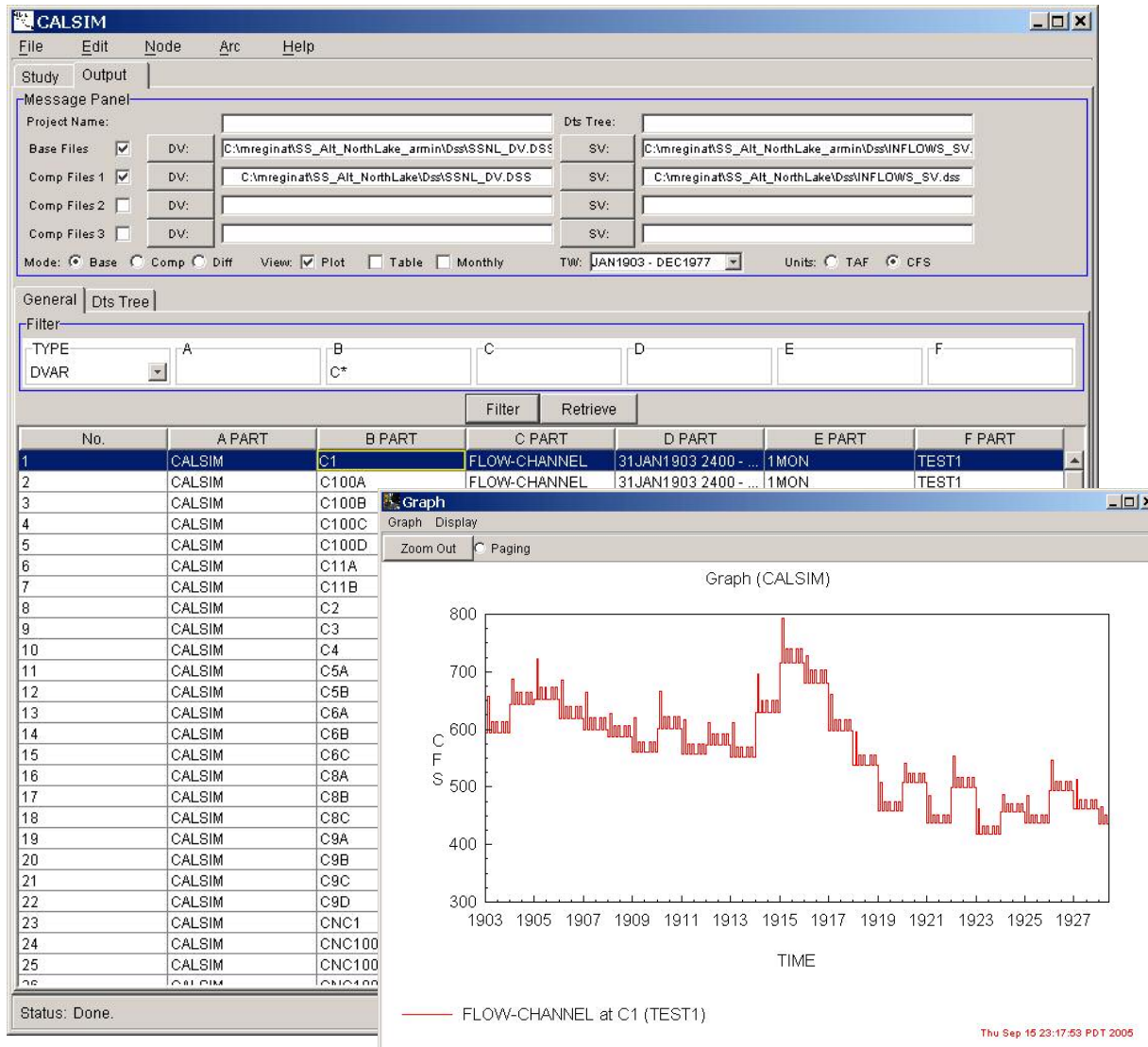
- ◆ **Includes functional relationships of evaporation suppression with increasing salinity**
- ◆ **Can achieve both water allocation targets and delivery water salinity targets**
- ◆ **Can incorporate goals to achieve targets within “sideboards”**
- ◆ **Includes initial refinement of annual inflows to monthly scale**

# **Generalized CALSIM Software**

- ◆ **Developed by DWR-USBR developed**
- ◆ **Extensively used on the SWP-CVP system; applications for American River, Klamath systems, etc.**
- ◆ **Software structure and information flow**
- ◆ **Linear programming techniques and simulation**
- ◆ **Objective function and priority weights**
- ◆ **WRESL simulation language**
- ◆ **Software requirements: Fortran90 compiler, XA solver**



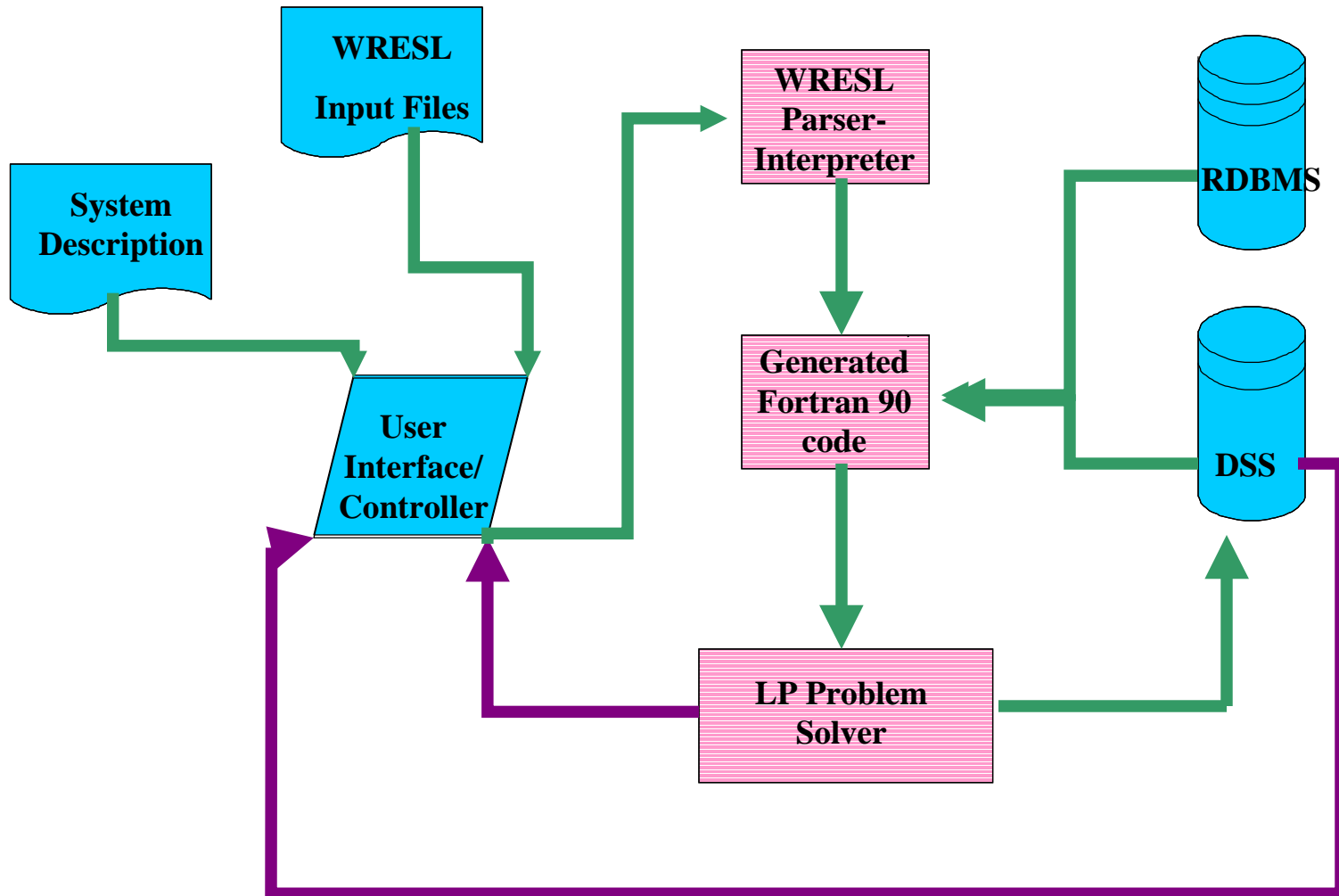
# CALSIM Model Description



- ◆ Water Resources Planning Model
- ◆ Network of nodes and arcs
- ◆ Graphical Interface
- ◆ LP solver for routing water
- ◆ WRESL language for specialized constraints
- ◆ Monthly or daily time step

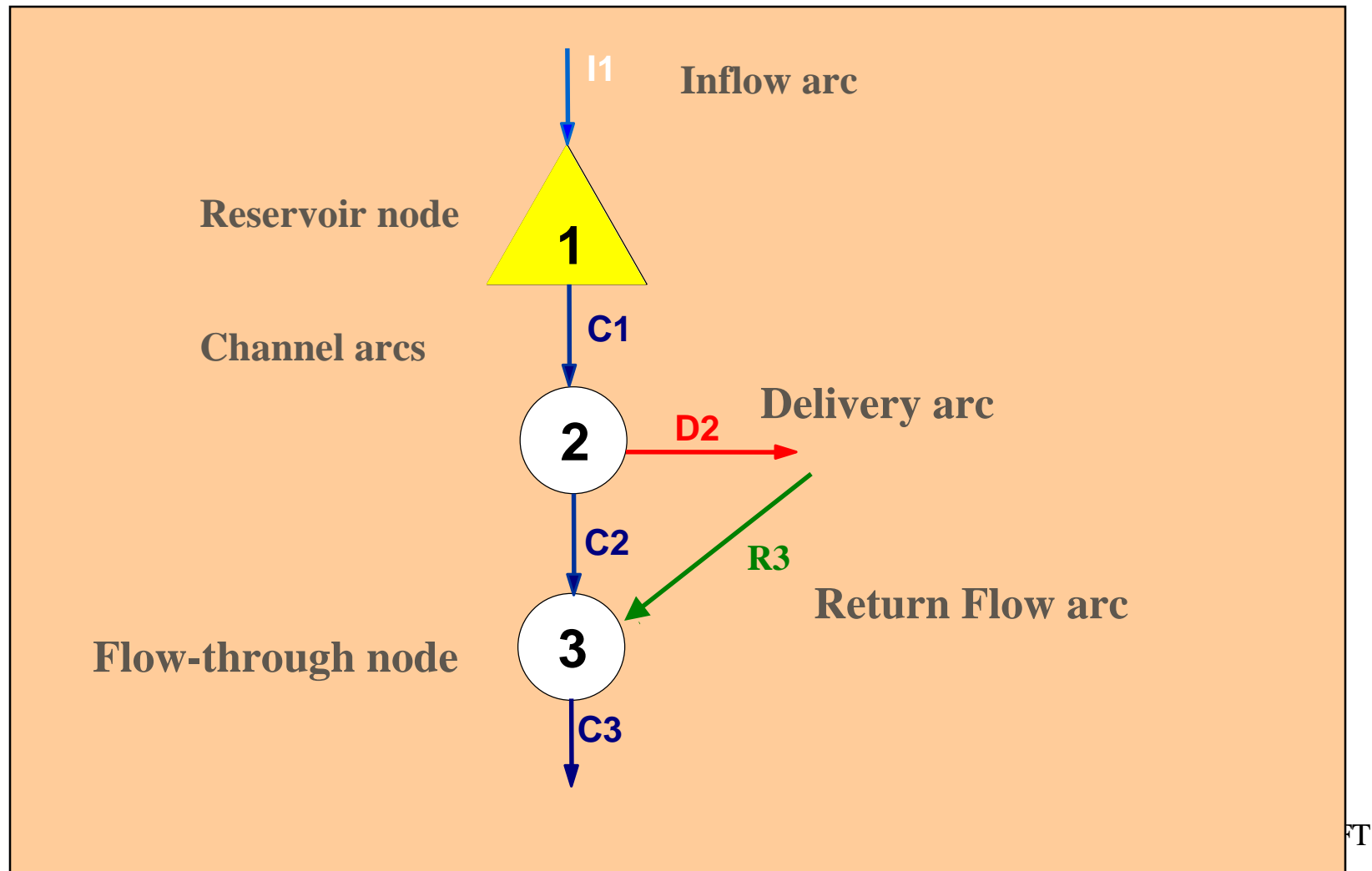
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# Model Components and Structure



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# Network Representation



# System Configuration

**CALSIM**

File Edit Node Arc Help

Study Output

General System Lookup Options Run/Result

Connectivity Reservoir Channel Delivery Return Inflow Weight

File Edit

Node	Arcs IN	Arcs OUT	Storage	Description
200	C9D			
	C100B	D200	S200	BRINE
	R200			
	C11B			
	C9C			
	I200A			
	C6C			
	C8C			
	C5B			
	I200B			
100	C4	C100		

Status: Done.

**CALSIM**

File Edit Node Arc Help

Study Output

General System Lookup Options Run/Result

Connectivity Reservoir Channel Delivery Return Inflow Weight

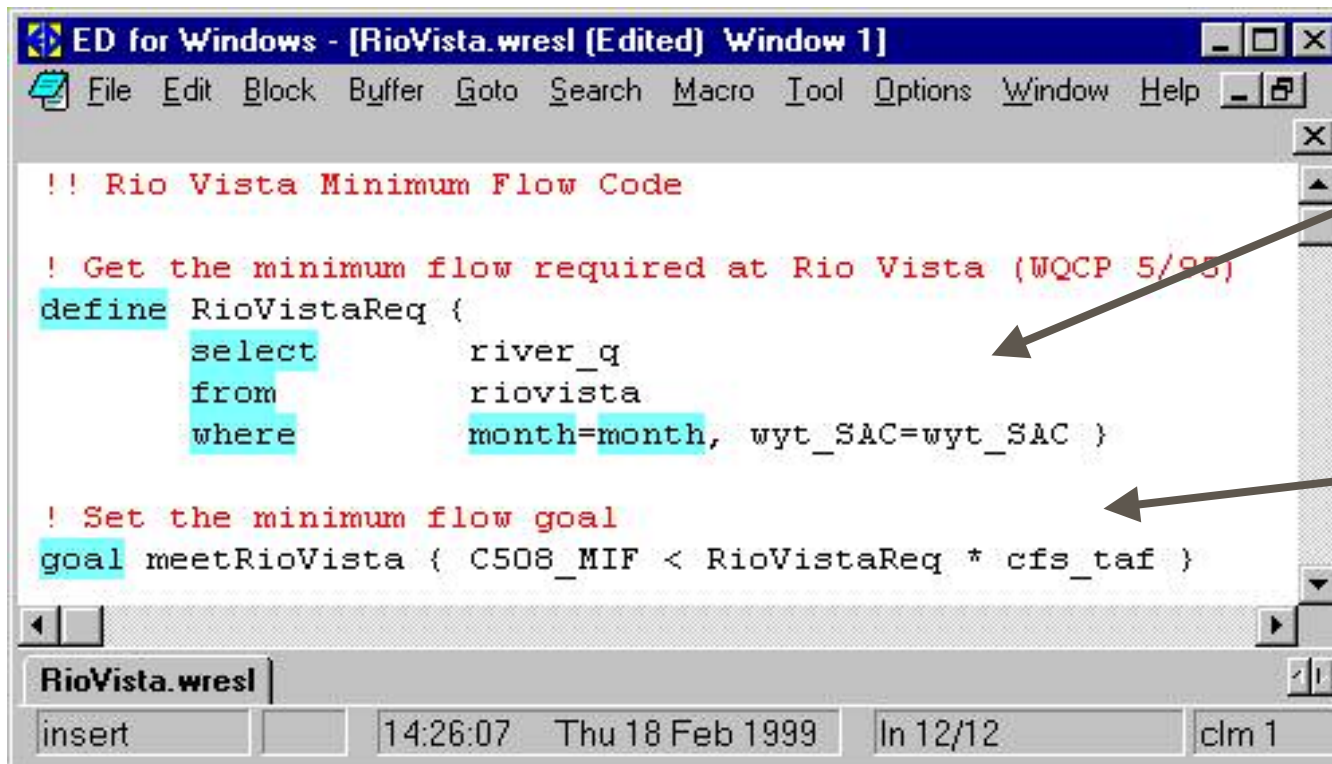
File Edit

Arc	Demand	Units	Description
D7	5	TAF	FW Habitat
D10	3	TAF	SW Habitat
D12	5.8333	TAF	
D100	0	CFS	
D200	0	CFS	

Status: Done.

# WRESL Language/Interface

- ◆ High-level language for rule specification
- ◆ Language interface to LP solver and time-series and relational data
- ◆ Simplicity: Two major statement types
- ◆ Flexibility: New standards, operational targets, etc.



The screenshot shows a window titled "ED for Windows - [RioVista.wresl (Edited) Window 1]". The menu bar includes File, Edit, Block, Buffer, Goto, Search, Macro, Tool, Options, Window, and Help. The code in the editor is as follows:

```
!! Rio Vista Minimum Flow Code

! Get the minimum flow required at Rio Vista (WQCP 5/95)
define RioVistaReq {
  select      river_q
  from        riovista
  where       month=month, wyt_SAC=wyt_SAC }

! Set the minimum flow goal
goal meetRioVista { C508_MIF < RioVistaReq * cfs_taf }
```

The status bar at the bottom shows "RioVista.wresl", "insert", "14:26:07 Thu 18 Feb 1999", "ln 12/12", and "clm 1".

## DEFINE:

Retrieving a flow standard from a lookup table

## GOAL:

Specifying a minimum flow constraint

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# **Linear Programming Solution**

- ◆ **Decision variables**
  - **Allocation of water for instream flow, delivery, and storage**
- ◆ **Objective function**
  - **Priority-based weights for allocation of water**
- ◆ **Constraints**
  - **Physical, operational, and institutional constraints on the system**
- ◆ **Efficient LP technique and solver route water for each time step**
- ◆ **Problem updated or reformulated each time step**

# Databases

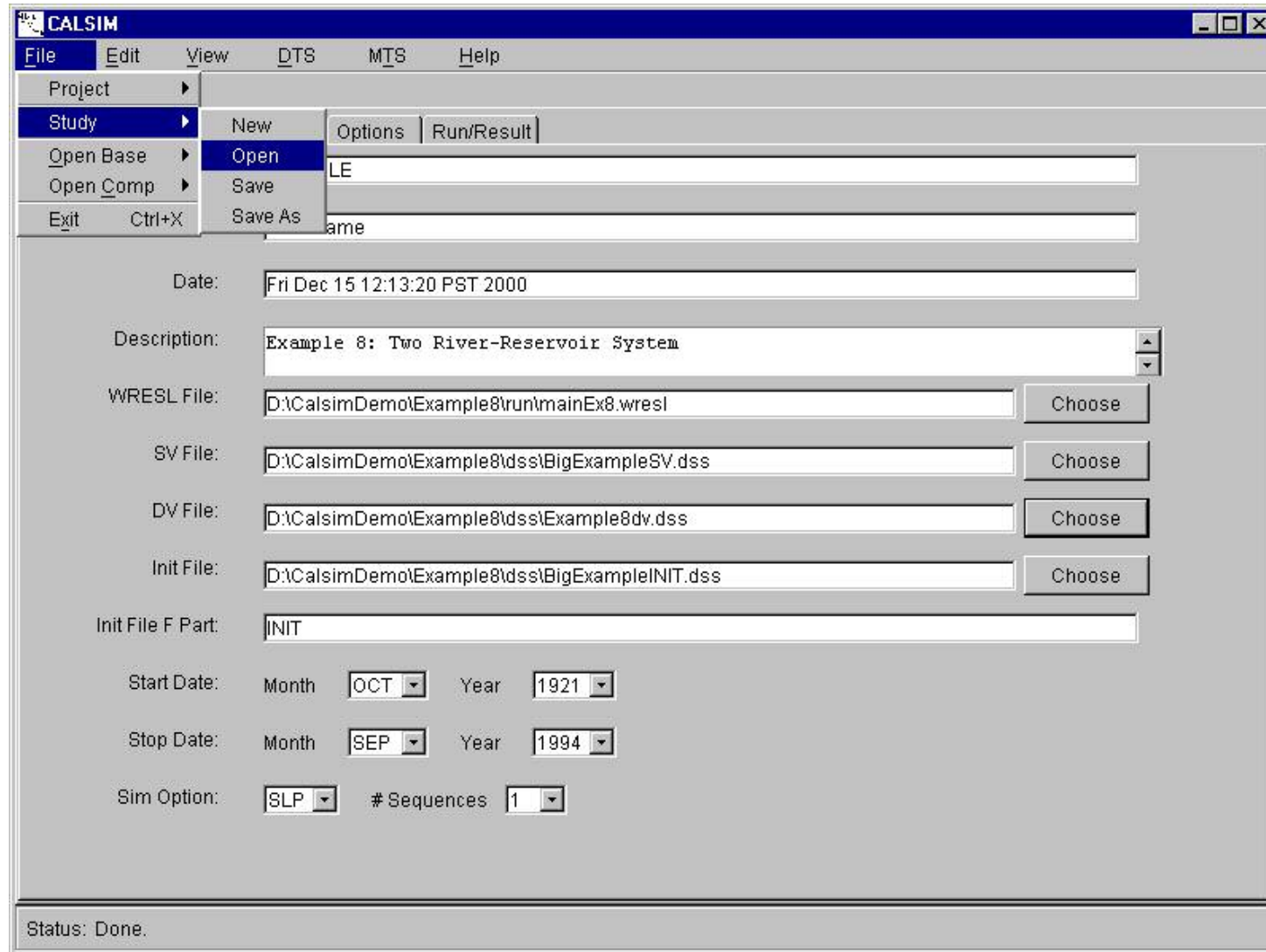
## ◆ Time-series Database

- HEC-DSS (USACOE Hydrologic Engineering Center)
- Metadata consist of a pathname (parts A-F)
- Efficient storage and retrieval of time-series data

## ◆ Relational “Database”

- Simple home-grown data retrieval system
- SQL-like statements can be specified in WRESL
- Relational data stored in structured text files

# User Interface: Study Control



**CALSIM**

File Edit View DTS MTS Help

Project

Study

Open Base

Open Comp

Exit Ctrl+X

New Options Run/Result

Open

Save

Save As

Date: Fri Dec 15 12:13:20 PST 2000

Description: Example 8: Two River-Reservoir System

WRESL File: D:\CalsimDemo\Example8\run\mainEx8.wresl Choose

SV File: D:\CalsimDemo\Example8\dss\BigExampleSV.dss Choose

DV File: D:\CalsimDemo\Example8\dss\Example8dv.dss Choose

Init File: D:\CalsimDemo\Example8\dss\BigExampleINIT.dss Choose

Init File F Part: INIT

Start Date: Month OCT Year 1921

Stop Date: Month SEP Year 1994

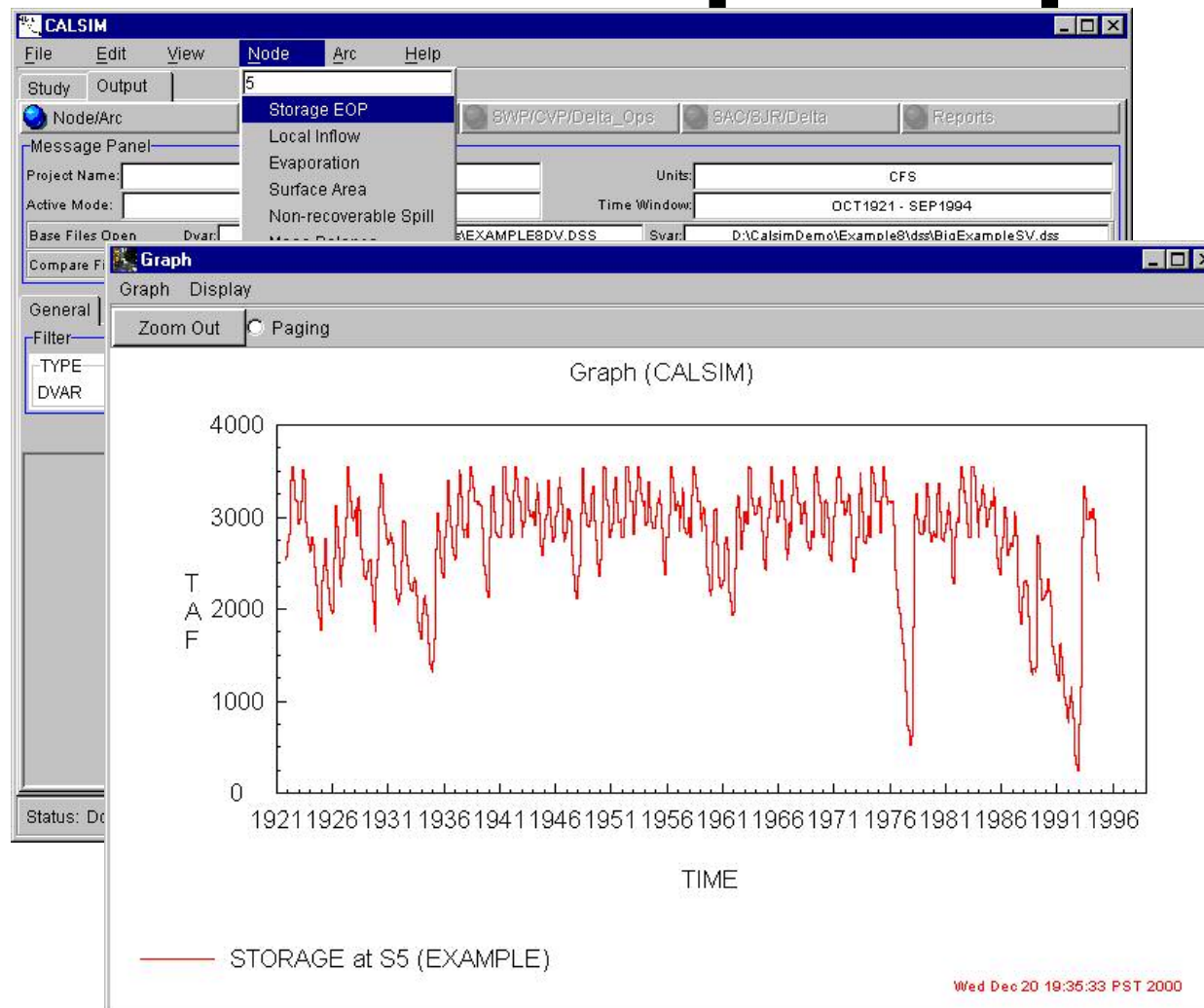
Sim Option: SLP # Sequences 1

Status: Done.

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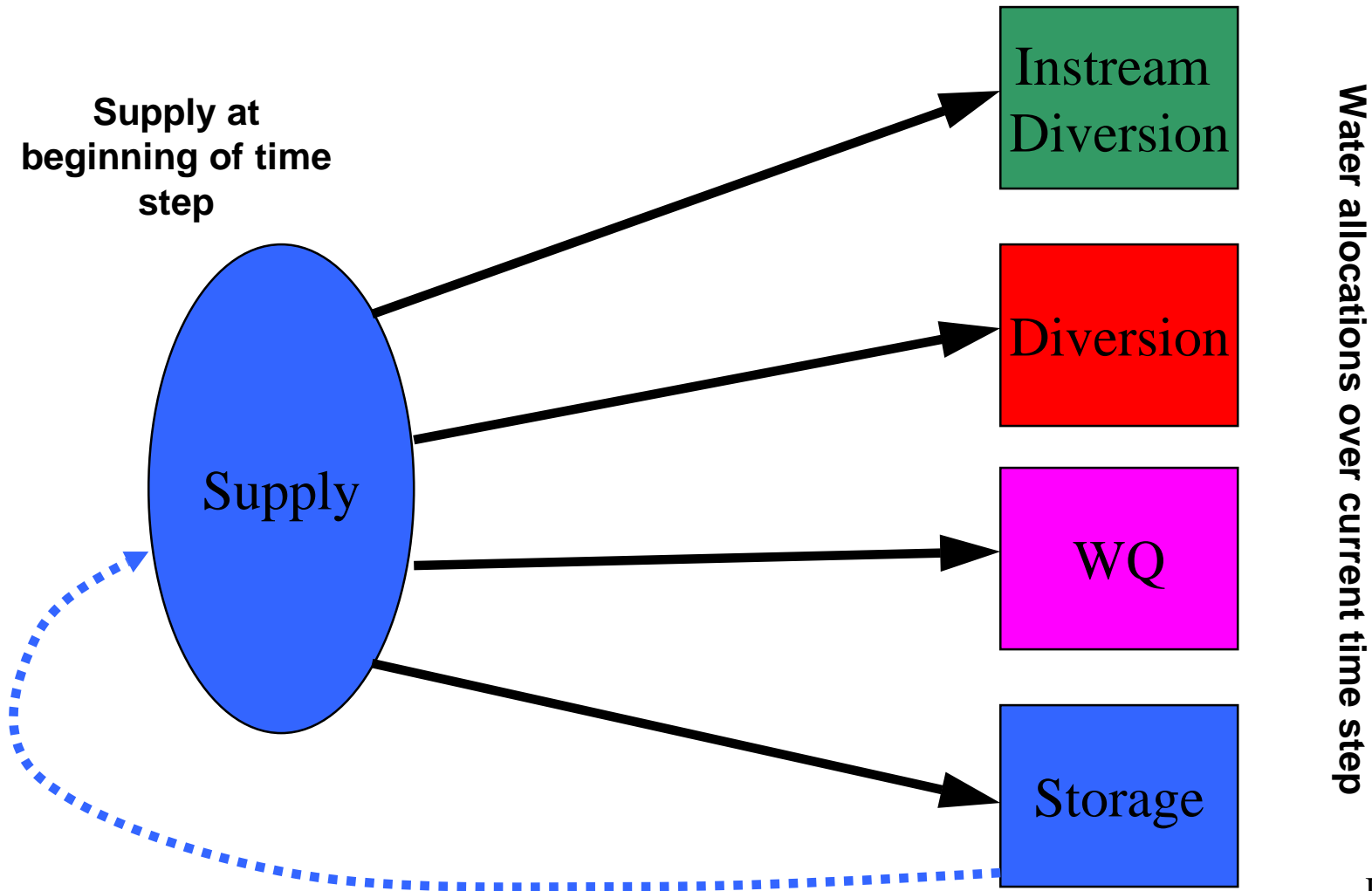


# User Interface: Input/Output Analysis



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# Water Allocation Modeling



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# **Linear Programming Model**

## **◆ Decision variables**

- Decisions available to planner and LP solver**

## **◆ Linear Objective function**

- Describes the objective of the model**
- Physical function or priority based**

## **◆ Linear Constraints**

- Requirements/limitations of the system**

# Objective Function

- ◆ Sum of linear terms involving cost coefficients (c) and decision variables (X)
- ◆ Either Maximize or Minimize
- ◆ Cost coefficients are constants in LP

$$\max Z = \sum_{i=1} c_i \cdot X_i$$

*or*

$$\max Z = c_1 \cdot X_1 + c_2 \cdot X_2 + c_3 \cdot X_3 + \dots + c_n \cdot X_n$$

# Constraints

- ◆ Linear combination of decision variables
- ◆ Inequalities or equalities
- ◆ General form

$$\sum_{j=1}^m a_{ij} \cdot X_j \leq b_i$$

◆ or

$$X_i \geq 0$$

$$a_{i1} \cdot X_1 + a_{i2} \cdot X_2 + a_{i3} \cdot X_3 + \dots + a_{im} \cdot X_m \leq b_i$$

$$X_1, X_2, X_3, \dots, X_m \geq 0$$

# Linear Programming Model

## ◆ Objective Function

$$\max Z = 140X_1 + 200X_2$$

## ◆ Constraints

$$X_1 + X_2 \leq 10$$

$$4X_1 + 3X_2 \leq 36$$

$$X_1 \leq 8$$

$$X_2 \leq 6$$

$$X_1, X_2 \geq 0$$

# **CALSIM Model Formulation**

- ◆ **Decision variables:**
  - **flow and storage arcs**
- ◆ **Objective function:**
  - **priority based cost coefficients (weights)**
- ◆ **Constraints:**
  - **physical, operational, or institutional**

# Objective Function

- ◆ Objective function is Maximized
- ◆ Weights ( $w$ ) on variables based upon priority
- ◆ Negative penalties ( $p$ ) multiply slack and surplus variables from “soft” constraints

$$\max Z = \sum_{i=1}^{nwt} (w_i \cdot X_i) + \sum_{j=1}^{npen} (-p_j \cdot x_j^+ | x_j^-)$$



# CALSIM Decision Variables

Decision Variable	Description	Example
$S_i$	end of period storage in node i	S1
$S_{ij}$	end of period storage in node i, zone j	S1_2
$C_i$	period average flow in channel arc i	C1
$C_{ij}$	period average flow in channel arc i, zone j	C1_MIF, C1_EXC
$D_i$	period average flow in delivery arc i	D6
$D_{ij}$	period average flow in delivery arc i, zone j	D6_MI, D6_AG
$R_i$	period average flow in return flow arc i	R7
$E_i$	period average flow in evaporation arc i	E1
$F_i$	period average flow in non-recoverable spill arc i	F1
$A_i$	end of period reservoir surface water area in node i	A1

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# CALSIM State Variables

State Variable	Description	Example
$I_i$	period average unregulated flow in inflow arc i	I1
$S_{i\text{level}j}$	storage in node i at level j	S1level4
$\text{relcap}_i$	maximum release capacity of reservoir i, applied at channel arc i	relcapC1
$C_{i\text{min}}$	absolute minimum flow in channel arc i	C5min
$C_{i\text{max}}$	maximum flow in channel arc i	C5max
$\text{minflow}_i$	minimum instream flow requirement for channel arc i	minflow_C4
$\text{demand}_{ij}$	demand for delivery arc i of type j	demand_D2_ag
$\text{rfactor}_i$	return flow fraction for return flow arc i resulting from a specified delivery arc	rfactor_R3
$\text{ev}_i$	period cumulative unit evaporation for node i	evap_S1
$\text{eff}_i$	recharge efficiency for a ground water node i resulting from a specified delivery arc	eff_D3
$X^{t-1}$	value of any decision variable X at any time previous to the current time period t	S1(-1), C5(-3)

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# CALSIM Constraints: Continuity

## ◆ Reservoir nodes:

$$\left(\sum I + \sum D + \sum C + \sum R\right)_{in} - \left(\sum D + \sum C + \sum E + \sum F\right)_{out} = S_i^t - S_i^{t-1}$$

## ◆ Flow-through nodes:

$$\left(\sum I + \sum D + \sum C + \sum R\right)_{in} - \left(\sum D + \sum C\right)_{out} = 0$$

# Channel Capacities & Return Flows

## ◆ Channel Capacities

$$C_i \min \leq C_i \leq C_i \max$$

## ◆ Return Flows

$$R_i = rfactor_i \cdot D_j$$

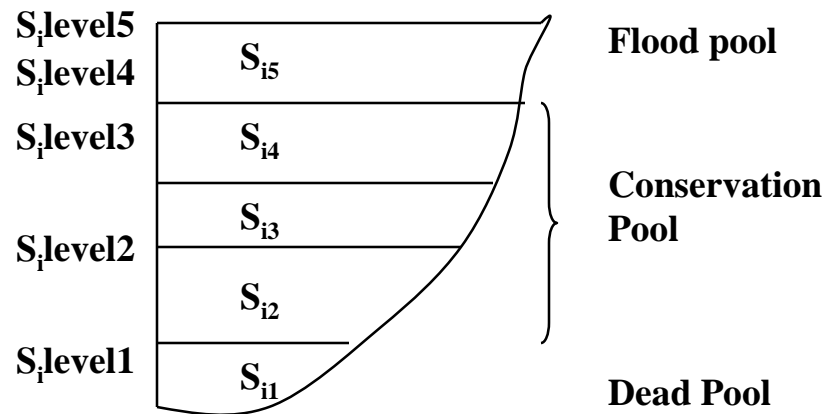
# Storage Zones

- ◆ Zone volume bounded by levels

$$0 \leq S_{ij} \leq S_i \text{level}_j - S_i \text{level}_{j-1}$$

- ◆ Sum of zones is total storage

$$S_i = \sum_{j=1}^{nzones} S_{ij}$$



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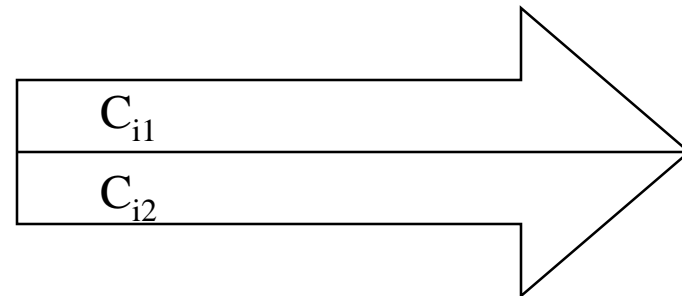
# Minimum Instream Flows

- ◆ Minimum instream flow zone bounded by flow target

$$0 \leq C_{ij} \leq \min flow_i$$

- ◆ Sum of zones is total channel arc

$$C_i = \sum_{j=1}^{nzones} C_{ij}$$



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# Deliveries

- ◆ Delivery zones bounded by current demand

$$0 \leq D_{ij} \leq demand_{ij}$$

- ◆ Sum of zones is total delivery arc

$$D_i = \sum_{j=1}^{ntypes} D_{ij}$$



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# Reservoir Release Capacity and Non-Recoverable Spills

- ◆ Releases bounded by the maximum permissible by outlet works

$$C_i \leq relcap_i$$

- ◆ Non-recoverable spills removed from water supply system

$$0 \leq F_i \leq \infty$$



# Reservoir Evaporation

- ◆ Evaporation is dependent on surface area

$$E_i = ev_i \cdot 0.5 \left[ A_i(S_i^{t-1}) + A_i(S_i^t) \right]$$

- ◆ Linearization of Area-Storage curve

$$A_i(S_i^t) \approx A_i(S_i^{t-1}) + coefEV_i(S_i^t - S_i^{t-1})$$

$$coefEV_i = \frac{\left[ A_i((1+c)S_i^{t-1}) - A_i((1-c)S_i^{t-1}) \right]}{2cS_i^{t-1}}$$

# **“Soft” Constraints**

- ◆ **User-specified constraints which may be violated at a cost (penalty)**
- ◆ **Goal minimizing the deviation between a constraint’s Left-hand-side (LHS) and Right-hand-side (RHS)**
- ◆ **Reformulated from “hard” to “soft” constraint by introducing auxiliary variables**
- ◆ **Auxiliary variables penalized in objective function**

# “Soft” Constraints

- ◆ Original “hard” constraint

$$S_A - S_B = 0$$

- ◆ Reformulated “soft” constraint

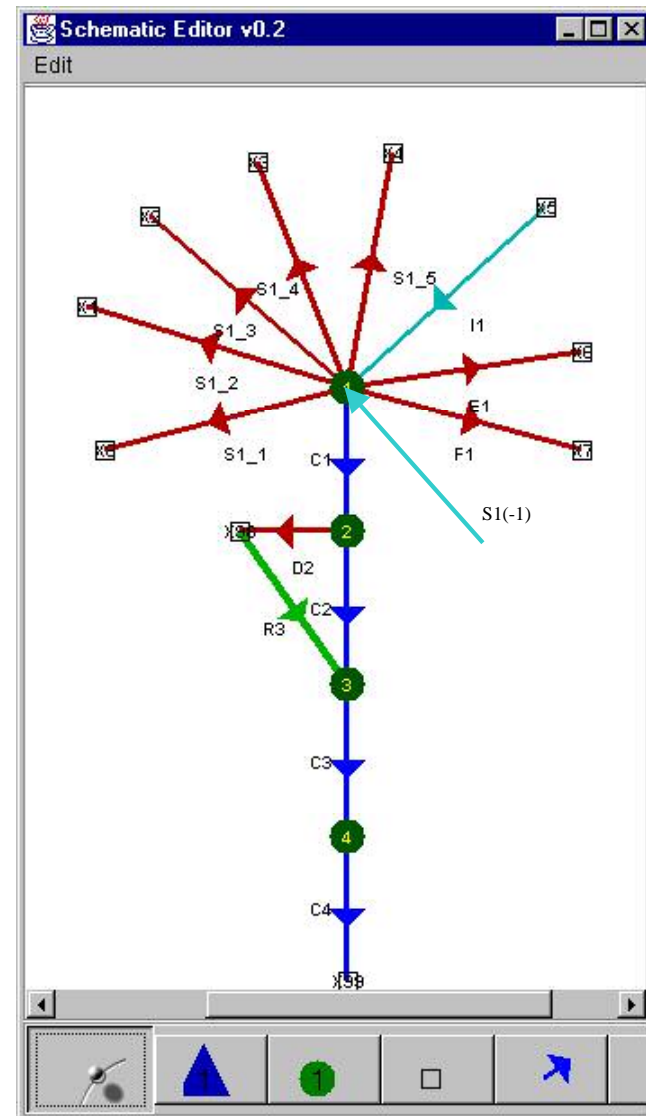
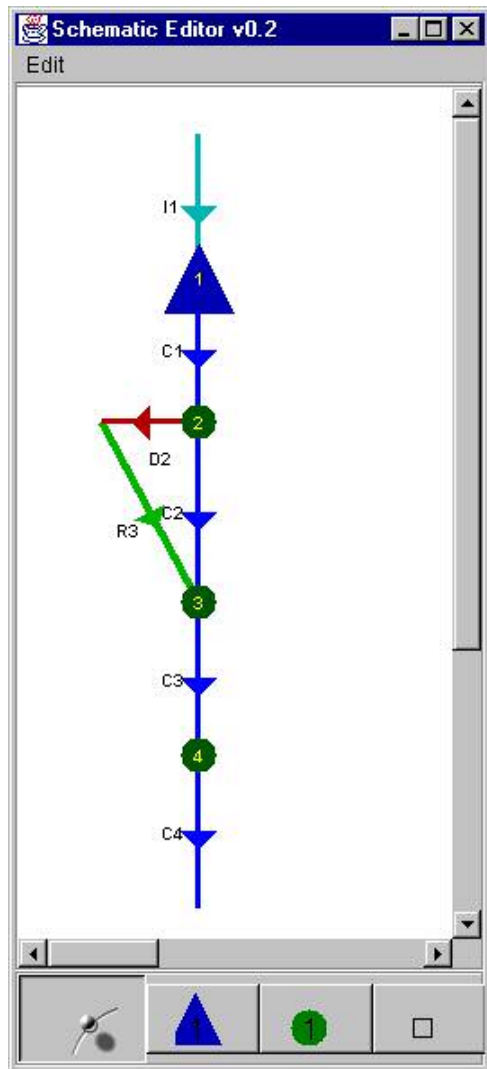
$$S_A - S_B + x^- - x^+ = 0$$

- ◆ Slack ( $x^-$ ) and surplus ( $x^+$ ) variables added

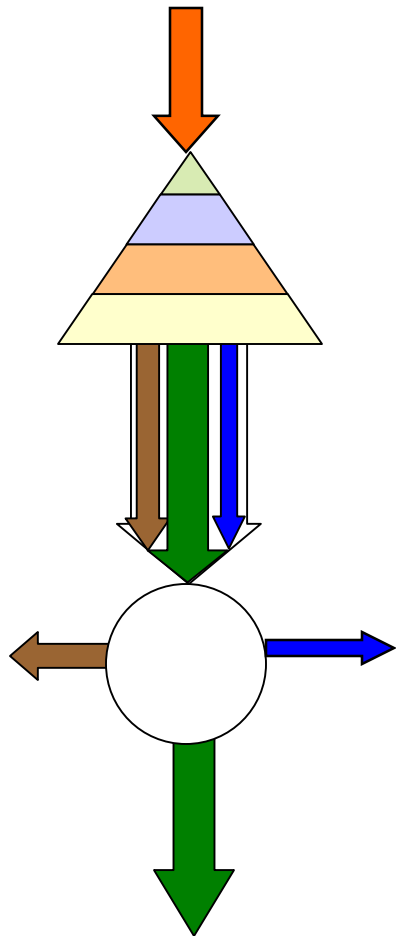
# **Integer Constraints**

- ◆ **Constraints involving integer decision variables**
- ◆ **Mixed integer problem solved by “branch and bound” technique**
- ◆ **May increase solution times by factor  $2^n$**
- ◆ **Commonly used to evaluate conditions with decision variables**

# Different Views (Network vs LP)



# Water Allocation



- **Storage: allocations to various zones**
- **Flow: allocations to various zones**
- **Deliveries: allocations to various zones**

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# WRESL Language Details

## ◆ Major statement types:

- SEQUENCE

- MODEL

- INCLUDE

- DEFINE

- GOAL

# **WRESL Language Details**

- ◆ **SEQUENCE statement**

- Specifies order in which models are simulated

- ◆ **MODEL statement**

- Specifies which operational rules are included in the current model

- ◆ **INCLUDE statement**

- Similar to Fortran include statement, inserts statements from other files in the current location



# **WRESL Language Details**

## **◆ DEFINE statement**

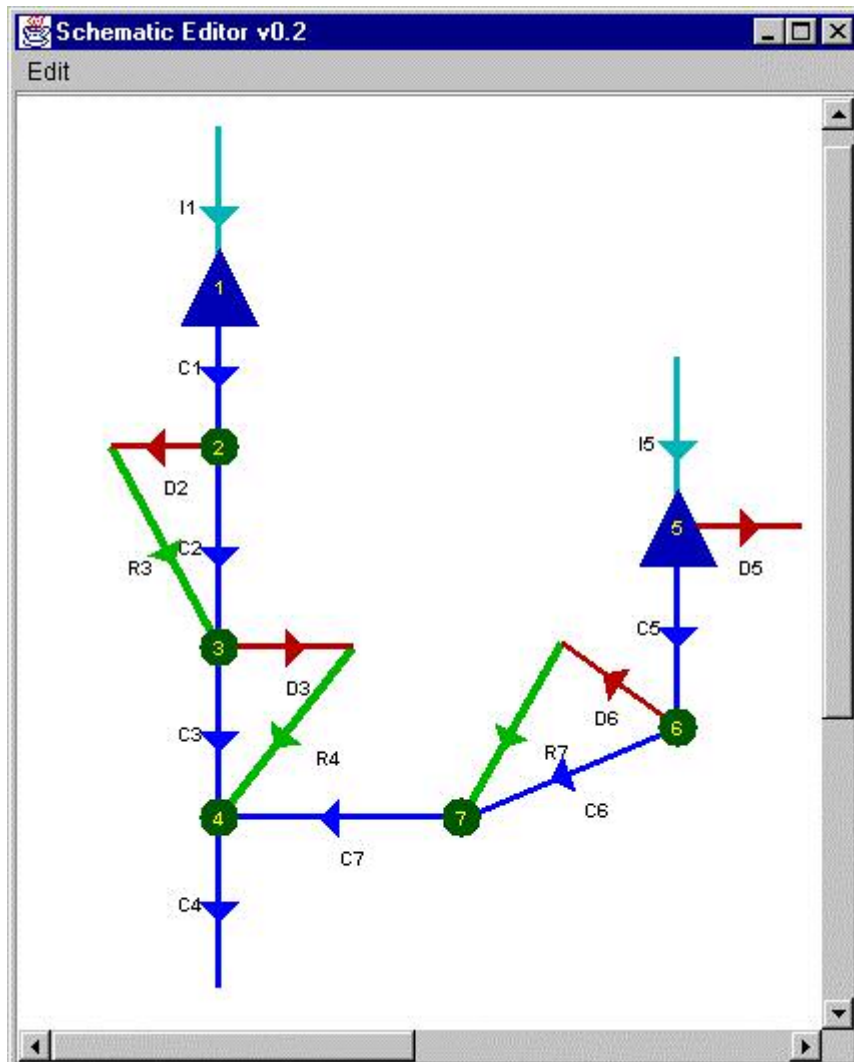
- Decision variable declarations**
- Constant, relational, or time-series state variable declarations and assignments**
- Intermediate computed state variables**
- Alias variable declaration and assignment**

# **WRESL Language Details**

## **◆ GOAL statement**

- Specify system operating constraints and targets**
- Directly translated into LP constraints**
- Short and long form**

# Simple River Network with CALSIM



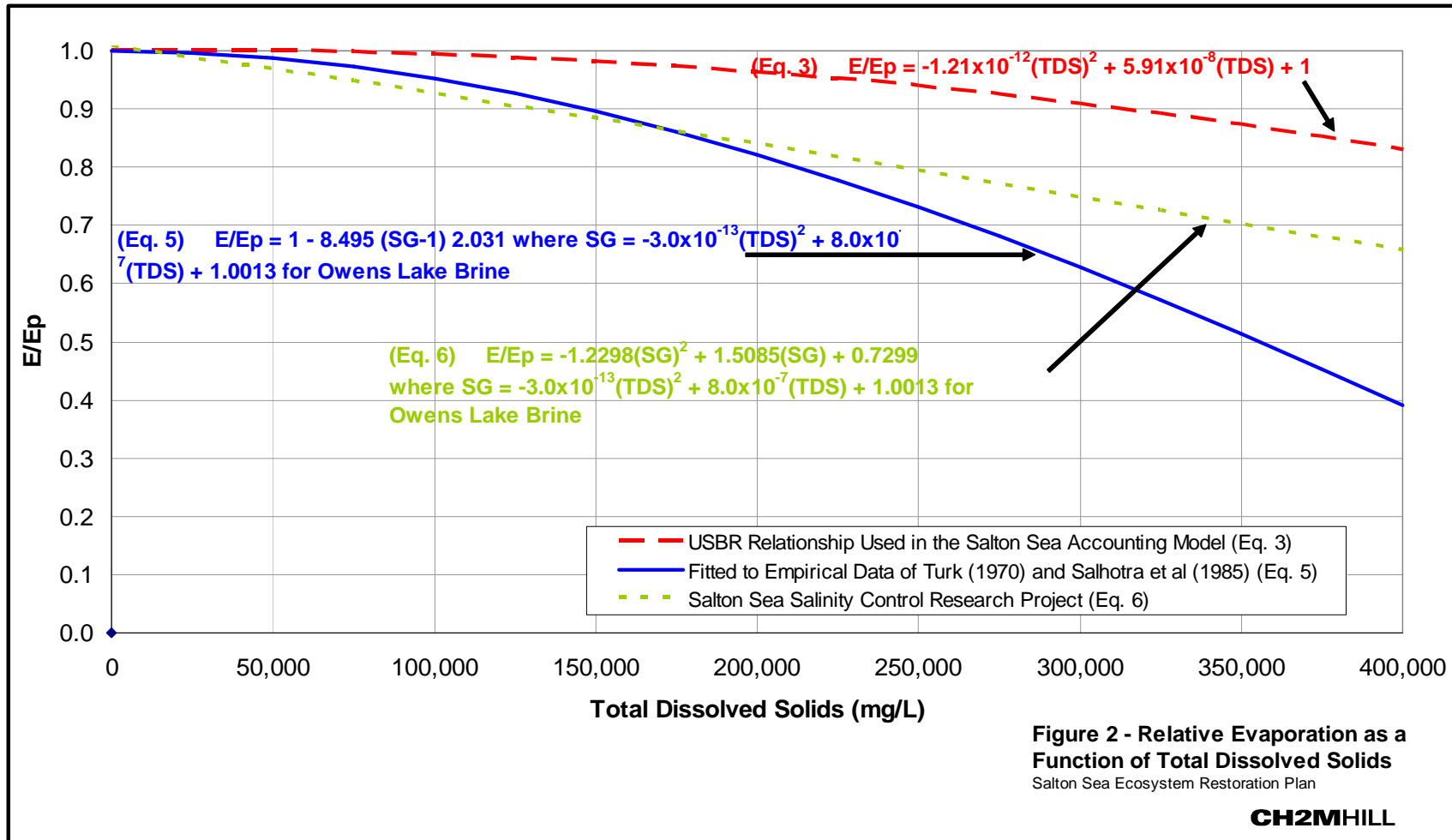
- ◆ Example network consisting of:
  - 2 reservoirs
  - 4 delivery points
  - 3 return flows
- ◆ Allocation goals set for deliveries and storage target
- ◆ Demo model setup and usage

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# **Enhancements Incorporated for Application to Salton Sea**

- ◆ **Evaporation suppression with increasing salinity**
- ◆ **Water quality algorithm**
- ◆ **Elevation and water quality targets**
- ◆ **Salt precipitation and re-dissolution (in progress)**
- ◆ **Stochastic wrapper (in progress)**

# Relative Evaporation as Function of TDS



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# Water Quality Algorithm

- ◆ Concentrations computed for every flow or storage arc in the system
- ◆ Conservative constituent with complete mixing at nodes assumed

$$C_o^t = \frac{\sum Q_i^t C_i^t}{\sum Q_i^t} \qquad C_s^t = \frac{\sum Q_i^t C_i^t + S^{t-1} C_s^{t-1}}{\sum Q_o^t + S^t}$$

- ◆ Previous cycle (internal time step iteration) concentration used to linearize the equation
- ◆ Updated each cycle and mass balance checks included

# **SALSA Model Formulation**

- ◆ **Network**
- ◆ **Components**
- ◆ **Mathematical formulation**
- ◆ **Targets**
- ◆ **Solution methods**
- ◆ **Input data and monthly downscaling**

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# **Modeling Salton Sea Restoration Components with SALSA**

- ◆ **Key components of restoration alternatives**
  - **Open water storage elements (SEA)**
  - **Natural treatment systems (NTS)**
  - **Mechanical treatment systems (MTS)**
  - **Habitat wetlands (HAB)**
  - **Air quality management (AQM) areas**
- ◆ **Consumptive use demands computed for NTS, HAB, and AQM components**
- ◆ **SEA components simulated as storage reservoirs**
- ◆ **Model allocates water to these components based on priority weights**

# Consumptive Demands and Delivery Targets

- ◆ NTS, HAB, AQM water requirements

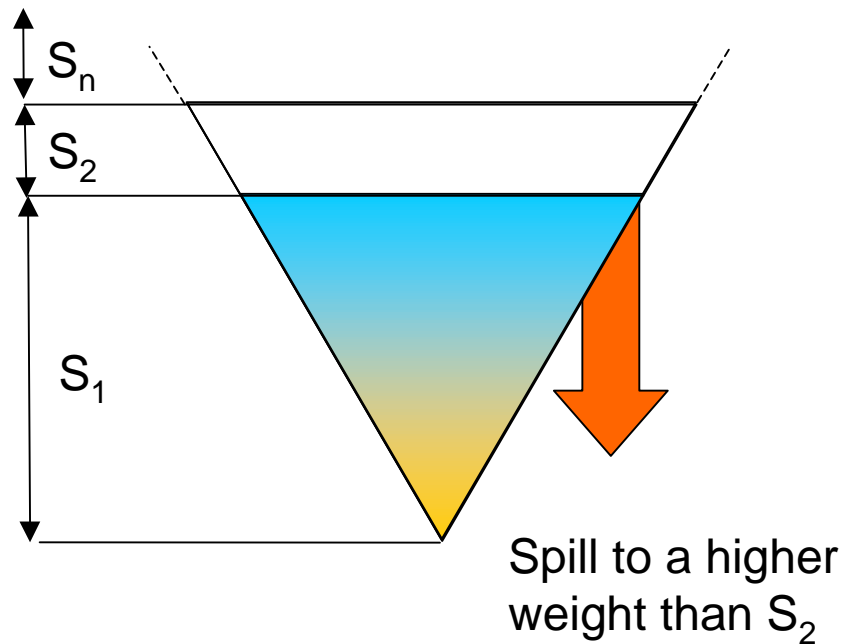
$$demand = \frac{ETo * Kc * A}{(1 - rfactor)}$$

ETo is reference ET, Kc is crop coefficient, A is irrigated area, and rfactor is the return flow fraction of delivered water

- ◆ Area is dynamically computed for AQM since exposed area is directly related to Sea and Brine water surface area
- ◆ Delivery arcs allocate water to these demands based on weights

$$0 \leq D_{ij} \leq demand_{ij}$$

# Elevation Targets



$$0 \leq S_{ij} \leq S_i level_j - S_i level_{j-1}$$

- ◆ **Weights drive the allocation of water to zones (or away from zones)**
- ◆ **Levels limit the size of storage zones**
- ◆ **Elevation targets are translated into storage targets through bathymetric tables**

# Sea Salinity Targets

- ◆ SEA salinity target set through constraint on constituent balance

$$\frac{\sum Q_i^t C_i^t - \sum Q_o^t C_o^t + S^{t-1} C_s^{t-1}}{S^t} \approx C^*$$

- ◆ Target is achieved through a penalized constraint (negative weight for non-attainment)
- ◆ Non-linear water quality constituent balance equation with Q, S, and C all potentially decision variables
- ◆ Linearized by using C from previous cycle and updating

# Delivery Salinity Targets

- ◆ Delivery salinity target set through constraint on constituent balance

$$\frac{\sum Q_i^t C_i^t}{\sum Q_i^t} \approx C^*$$

- ◆ Target is achieved through a penalized constraint (negative weight for non-attainment)
- ◆ Non-linear water quality constituent balance equation with Q and C both potentially decision variables
- ◆ Linearized by using C from previous cycle and updating

# **Solution Method**

- ◆ **Model is configured to simulate multiple cycles on a monthly time step**

- **Cycle 1**

- ❖ delivery and storage targets
- ❖ water allocation

- **Cycle 2**

- ❖ salinity targets
- ❖ water allocation constrained to delivery and storage results from cycle 1 maintained

- **Cycle 3 ...n**

- ❖ same as 2 with updated water quality concentrations

# **Input Data**

## **◆ Initial conditions**

- volume in each storage node**
- concentration in each storage node**

## **◆ Time-series data**

- inflows**
- inflow TDS concentrations**
- ETo, Kc data (can be patterned for relational)**

## **◆ Relational data**

- bathymetry**

# **Monthly Downscaling**

- ◆ **All annual hydrologic input requires downscaling to monthly time interval**
- ◆ **Initial method applies an average monthly pattern to the annually varying inflows and evaporation**
- ◆ **More comprehensive approach in progress to select patterns based on hydrologically-similar years in the historical record**
- ◆ **Projections outside of the historical realm will require pattern reshaping**



# **SALSA Model Demonstration**

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# **Deterministic vs Stochastic Applications**

- ◆ **Current model is deterministic**
  - **one hydrologic trace is simulated**
  - **results in one trace of elevation, salinity, etc**
  - **does not account for variability or uncertainty**
- ◆ **Modification to model for stochastic version has begun**
  - **multiple hydrologic traces considering variability and uncertainty**
  - **results in many (hundreds/thousands) traces of simulation results**
  - **allows statistical analysis of results**

# **Future Model Development Tasks**

- ◆ **Internal QA of algorithms**
- ◆ **Calibration 1950-99 historical period**
- ◆ **Validation ?**
- ◆ **Refine monthly downscaling methods**
- ◆ **Application to all major configurations being considered**
- ◆ **Stochastic wrapper**
- ◆ **Greater automation**

# Discussion

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